A Model for Educating Systems Engineers

Thomas B. Hilburn
Department of Electrical, Computer,
Software, and Systems Engineering
Embry-Riddle Aeronautical University
Daytona Beach, FL
hilburn@erau.edu

Alice Squires
School of Systems and Enterprises,
Stevens Institute of Technology
One Castle Point
Hoboken, NJ
alice.squires@stevens.edu

Raymond Madachy
Graduate School of Engineering and
Applied Sciences
Naval Postgraduate School
Monterey, CA
rjmadach@nps.edu

Abstract— **This paper discusses a model for developing a master's degree curriculum for systems engineering professionals. The model provides guidelines and recommendations that can be used for developing a new program or for modifying an existing program. The model was developed as part of the BKCASE (Body of Knowledge and Curriculum to Advance Systems Engineering) project to develop a guide to the Systems Engineering Body of Knowledge (SEBoK) and a Graduate Reference Curriculum for Systems Engineering (GRCSE). This paper describes the content of the SEBoK used to drive the core body of knowledge in a systems engineering program, and discusses the GRCSE purpose, organization, content, development process, and implementation.**

Keywords - systems engineering body of knowledge; systems engineering education; systems engineering graduate reference curriculum

I. INTRODUCTION

The initial education of systems engineers typically begins at the master's level. Entering students normally have an undergraduate degree in another engineering field and often have experience as a practicing engineer. As an academic discipline, system engineering is in its infancy: compared to more traditional engineering fields there are few systems engineering master degree programs (70 or so in the US); the content and organization of the systems engineering body of knowledge is not well-defined and does not enjoy universal agreement; and there is no reference curriculum for systems engineering.

The BKCASE (Body of Knowledge and Curriculum to Advance Systems Engineering) project [1] is three-year project, begun in September 2009 and sponsored by Department of Defense, to develop a guide to the Systems Engineering Body of Knowledge (SEBoK) and a Graduate Reference Curriculum for Systems Engineering (GRCSE). There is more information about BKCASE and a link to the latest version of GRCSE at http://www.bkcase.org. This paper describes the purpose, content and current status of the development of GRCSE. The 0.5 version of GRCSE

has been completed and the final 1.0 version is expected to be complete in December 2012 [2].

II. SEBoK DEVELOPMENT

The work on the SEBoK [3] is nearing completion and is expected to be finalized in September 2012 and then provided to professional societies for future sustainability. The SEBoK is intended to define and organize the systems engineering discipline, including its vocabulary, concepts, methods, processes, practices, and tools. It does not attempt to provide detailed coverage of systems engineering, but is rather a guide for users in finding and understanding the literature about systems engineering that has been separately published in books, articles, websites, and other generally accessible resources. One set of primary intended users of the SEBoK are faculty who are developing systems engineering courses and curricula. As might be expected, the SEBoK is intended as a principal source document for the development of GRSCE. The Appendix outlines the contents of the SEBoK.

III. GRCSE OVERVIEW

The purpose of GRCSE is to assist in the development of new master's SE programs and to improve existing SE graduate programs. The principal GRCSE stakeholders are universities, students, graduates, employers, and systems customers and users. GRCSE is designed to support a systems-centric program and a professional master's degree focused on developing student ability to perform systems engineering tasks and roles.

The BKCASE author team consists of invited experts from academia, industry, government, and various professional associations. These authors have followed an incremental approach to create the SEBoK and GRCSE. GRCSE development has depended on many sources, detailed in the GRCSE list of references. Two sources strongly influenced the organization and methodology of GRCSE: an International Council on Systems Engineering (INCOSE) published reference

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **MAR 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**
4. TITLE AND SUBTITLE **A Model for Educating Systems Engineers**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Stevens Institute of Technology,School of Systems and Enterprises,Castle Point,Hoboken,NH,07030**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
6th Annual IEEE Systems Conference (SysCon) Vancouver, Canada, 19-22 March 2012.

14. ABSTRACT

This paper discusses a model for developing a master?s degree curriculum for systems engineering professionals. The model provides guidelines and recommendations that can be used for developing a new program or for modifying an existing program. The model was developed as part of the BKCASE (Body of Knowledge and Curriculum to Advance Systems Engineering) project to develop a guide to the Systems Engineering Body of Knowledge (SEBoK) and a Graduate Reference Curriculum for Systems Engineering (GRCSE). This paper describes the content of the SEBoK used to drive the core body of knowledge in a systems engineering program, and discusses the GRCSE purpose organization, content, development process, and implementation.

15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

curriculum framework for a graduate program in SE [4], and the Graduate Software Engineering 2009 (GSwE2009) [5], sponsored by DOD and now supported by the Association for Computing Machinery (ACM) and the Institute for Electrical and Electronics Engineers (IEEE) Computer Society. Also, at the beginning of GRCSE development the project team conducted an international survey of Master of SE (MSE) programs, soliciting information about the MSE programs' attributes, outcomes, admission requirements, and curriculum structure and content.

The GRCSE project team met in workshops approximately every three months between December 2009 and October 2010, leading to the limited-review release of v0.25 of both GRCSE and SEBoK. GRCSE v0.25 was released in December 2010 to selected members of the SE community with the invitation to review and provide the necessary feedback to develop subsequent versions. This feedback was received and forms the basis of the current version, v0.5. GRCSE v0.5 is available at http://www.bkcase.org/grcse-05/. Version 1.0 is scheduled for release in late 2012.

As part of the GRCSE project formation, the project team established the following set of guiding principles to provide a foundation for all GRCSE development activities:
- SEBoK, Version 0.5, serves as an important input to GRCSE.
- SE interacts with other disciplines, some of which provide important foundation concepts for SE. These disciplines are integrated into GRCSE as appropriate.
- Existing SE programs are diverse.
- SE is by nature a practical discipline and therefore students must learn how to integrate theory and practice. This is discussed in the outcomes and objectives of GRCSE.

Subsequent sections discuss the contents of the key components of GRCSE.

IV. STUDENT OUTCOMES

Most academic programs are now "outcomes-based"; that is, a program's curriculum is developed around the competencies that are expected of a graduate upon completion of the program. The GRCSE team developed thirteen student outcomes, based on consultation and interaction with the SE community, including both faculty and practitioners. The following five outcomes illustrate their nature:
- (Outcome 1) Achieve designated Bloom's levels [6] of attainment for each SEBoK topic contained within the GRCSE core body of knowledge

(described in Section VII).
- (Outcome 4) Demonstrate the ability to perform SE activities in one application domain, such as defense, aerospace, finance, medical, transportation, or telecommunications.
- (Outcome 5) Apply systems engineering principles to address one application type, such as safety-critical or embedded systems, or one property, such as security, agility, or affordability.
- (Outcome 7) Be an effective member of a multi-disciplinary team, effectively communicate both orally and in writing, and lead in one area of system development, such as project management, requirements analysis, architecture, construction, or quality assurance.
- (Outcome 10) Be able to learn new models, techniques, and technologies as they emerge, and appreciate the necessity of such continuing professional development.

V. PROGRAM OBJECTIVES

Objectives are important statements about the future professional capabilities of the graduates of a program. They are used to set the student outcomes and to tailor the offerings of a program to support the career expectations of the student and employer communities.

GRCSE recommends that all programs set formal objectives to help define the top-level requirements for their programs and offers the following sample objectives, which could be tailored to meet the special needs of its stakeholders.
- Effectively analyze, design, and implement feasible, suitable, effective, supportable, affordable, and integrated solutions throughout the life cycle of systems of systems, enterprises, services, and products.
- Successfully assume a variety of roles in multi-disciplinary teams of diverse membership, including technical expertise and leadership at various levels.
- Demonstrate professionalism. Grow professionally through continued learning and involvement in professional activities. Contribute to the growth of the profession. Contribute to society through ethical and responsible behavior.
- Communicate (read, write, speak, listen, and illustrate) effectively in oral, written, and newly developing modes and media, especially with stakeholders and colleagues.

VI. ENTRANCE EXPECTATIONS

For any graduate program, the prior accomplishments of entering students are critical to success. Attainment of program objectives and student outcomes depends, in part, on student capabilities when they enter the

program. GRCSE specifies the following student expectations to support outcome achievement:

- The equivalent of an undergraduate degree in engineering, the natural sciences (biology, chemistry, physics, astronomy, and earth sciences), mathematics, or computer science;
- At least two years of practical experience in some aspect of systems engineering. This experience should include participation in teams and involvement in the life cycle of a system, subsystem, or system component.
- Demonstrated ability to effectively communicate technical information, both orally and in writing, in a program's language of instruction.

The expectations recommended here are not admission requirements; but, deviations from these expectations may require lengthening the program to compensate for gaps in student ability and to enable students to achieve the recommended outcomes. A student may compensate for the lack of a formal education by more extensive prior experience or by taking an internship or pursue some other means to gain that experience while in the degree program. A university can offer leveling courses to provide expected knowledge or skill that a student may lack.

VII.   CORE BODY OF KNOWLEDGE (CORBOK)

The Core Body of Knowledge (CorBoK) for GRCSE identifies the topic areas that address the skills, knowledge, and abilities a student should learn to achieve the expected outcomes upon receiving a master's degree in systems engineering. The knowledge in the CorBoK includes topic areas covered in the SEBoK (see the Appendix). For each knowledge element, a level of mastery is defined using Bloom's taxonomy.

The CorBoK is structured in two parts, foundation and concentration. Foundation knowledge comprises the broad set of topics deemed essential for all systems engineers. In addition, each student is also expected to choose and acquire in-depth knowledge in an area of concentration.

The expectation for concentration knowledge supports GRCSE outcome 7 (see Section IV), which specifies "lead in one area of system development, such as project management, requirements analysis, architecture, construction, or quality assurance". To illustrate this concept, GRCSE provides two examples of concentration areas: Systems Engineering Management (SEM) and Systems Design and Development (SDD). Table 1 illustrates how the CorBoK is depicted for three of the SEBoK knowledge areas (KAs). Table 2 shows how the SEBoK major

sections are distributed across the two example concentrations, SEM and SDD.

Table 1: CorBoK Description (for 3 KAs)

SEBoK Knowledge Area (KA)	Topic	Foundation	SEM	SDD
System Realization	System Implementation	Application		Analysis
	System Integration	Application		Analysis
	System Verification and Validation	Application		Analysis
System Deployment and Use	System Deployment	Comprehension		Application
	Operation of the System	Comprehension		Application
	System Maintenance	Comprehension		Application
	Logistics	Comprehension		Application
Systems Engineering Management	Planning	Comprehension	Analysis	
	Assessment and Control	Comprehension	Analysis	
	Risk Management	Comprehension	Analysis	
	Measurement	Comprehension	Analysis	
	Decision Management	Comprehension	Analysis	
	Configuration Management	Comprehension	Analysis	
	Information Management	Comprehension	Analysis	
	Quality Management	Comprehension	Analysis	

Table 2: CorBoK Distribution for SEM and SDD

SEBoK Part	Foundation/ SEM %	Foundation/ SDD %
Part 2: Systems	12%	12%
Part 3:Systems Engineering and Management	56%	56%
Part 4: Applications of Systems Engineering	10%	10%
Part 5: Enabling Systems Engineering	10%	4%
Part 6: Related Disciplines	12%	18%
Total Distribution %	100%	100%

VIII.   CURRICULUM ARCHITECTURE

The curriculum architecture is organized into six elements: preparatory knowledge, foundation knowledge, concentration knowledge, domain-specific knowledge, program-specific knowledge, and a mandatory capstone experience. The relationship between these elements is portrayed in Figure 1.

The preparatory knowledge forms the foundation for the curriculum. GRCSE describes a set of topics that

are necessary for success in a GRCSE based curriculum. These topics in engineering, math and science, and communication correspond to the background an entering student should possess in order to achieve the GRCSE recommended outcomes.

The foundation and concentration material is intended to constitute about half the coursework for the degree, leaving the remaining portion of the program for program-specific work; however, this does not preclude the CorBoK topics from being addressed in other parts of the curriculum, including the capstone experience.

GRCSE points out that the capstone can be implemented through a variety of methods, including individual or team capstone projects or a practicum. The specified curriculum content may be distributed through multiple courses, such as by performing system architecture and design at increasing levels of detail. A master's thesis that meets the expectations for the capstone experience is also a possible implementation.
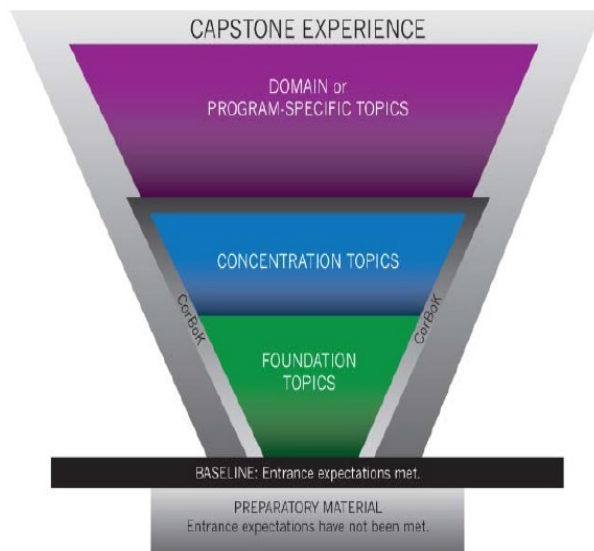

Figure 1: GRCSE Curriculum Architecture

IX. GRCSE IMPLEMENTATON

GRCSE (and other sources [4], [7]) provide ideas and suggestions for implementing its guidance and recommendations into a new or existing systems engineering program. This includes the following:

- **Assessing Program Maturity** – For an existing program the first step would be to assess the extent to which the current program aligns with GRCSE elements [6].
- **Developing and Assessing Program Objectives** – Guidance is provided on how to determine program objectives and develop an objectives assessment and evaluation process.
- **Developing and Assessing Student Outcomes** – Guidance is provided on how to determine student outcomes and develop an outcomes assessment and evaluation process.
- **Designing Curriculum Components** – GRCSE offers ideas for using the student outcomes and the curriculum body of knowledge to design and assemble curriculum components: supporting materials, course structure and content, and capstone experiences.

X. FINAL THOUGHTS

The GRCSE document is just the initial step in the set of activities needed to advance professional systems engineering through the enhancement of graduate systems engineering programs. In order for GRCSE to be considered a successful product, the model must be available, understood by the targeted academic and industrial communities, viewed as a key reference for systems engineering curriculum development, and actually used in the development and modification of systems engineering curricula. The continued support of GRCSE by the INCOSE and the IEEE is a critical step in advancing these success goals.

We encourage those who are stakeholders in professional systems engineering education (managers, practitioners, educators) to become involved in the GRCSE effort: download the full document; read and study it; share your views of it with your colleagues; promote or support an effort to create a new program or enhance an existing program using GRCSE guidance.

APPENDIX SEBoK VERSION 0.5: OUTLINE

The following is an outline of the Knowledge Areas (KAs) and topics addressed in [3]:

Part 1: SEBoK 0.5 Introduction
- Scope of the SEBoK
- Structure of the SEBoK
- Systems Engineering: Historic and Future Challenges
- Systems Engineering and Other Disciplines
- SEBoK Users and Uses
- SEBoK Evolution
- Acknowledgements

Part 2: Systems
- Knowledge Area: Systems Overview
- Knowledge Area: System Concepts
- Knowledge Area: Types of Systems
- Knowledge Area: Representing Systems with Models
- Knowledge Area: Systems Approach
- Knowledge Area: Systems Challenges

Part 3: Systems Engineering and Management

- Knowledge Area: Life Cycle Models
- Knowledge Area: System Definition
- Knowledge Area: System Realization
- Knowledge Area: System Deployment and Use
- Knowledge Area: Systems Engineering Management
- Knowledge Area: Product and Service Life Management
- Knowledge Area: Systems Engineering Standards

Part 4: Applications of Systems Engineering
- Knowledge Area: Product Systems Engineering
- Knowledge Area: Service Systems Engineering
- Knowledge Area: Enterprise Systems Engineering
- Knowledge Area: Systems of Systems (SoS)

Part 5: Enabling Systems Engineering
- Knowledge Area: Systems Engineering Organizational Strategy
- Knowledge Area: Enabling Businesses and Enterprises to Perform Systems Engineering
- Knowledge Area: Enabling Teams to Perform Systems Engineering
- Knowledge Area: Enabling Individuals to Perform Systems Engineering

Part 6: Related Disciplines
- Knowledge Area: Systems Engineering and Software Engineering
- Knowledge Area: Systems Engineering and Project Management
- Knowledge Area: Systems Engineering and Specialty Engineering

Part 7: Systems Engineering Implementation Examples

The full SEBoK 0.5 outline is provided online at: http://sebokwiki.org/index.php/SEBoK_0.5_Outline.

REFERENCES

[1] A. Squires, T. Ferris, D. Olwell, N. Hutchison, S.Enck, A. Pyster, and D. Gelosh, "Work in process: A body of knowledge and curriculum to advance systems engineering (BKCASE™)," in *2011 IEEE International Systems Conference Proceedings*, Montreal, Quebec, Canada, April 4-7, 2011, pp. 250-255.

[2] A. Pyster, D. Olwell, A. Squires, N. Hutchison, S. Enck, Eds.,; T. Ferris, Lead Author. "Graduate Reference Curriculum for Systems Engineering. Version 0.5." Stevens Institute of Technology, Hoboken, NJ, USA. Released for public review 2011.

[3] A. Pyster, D. Olwell, A. Squires, N. Hutchison, S. Enck, Eds., "A Guide to the Systems Engineering Body of Knowledge (SEBoK). Version 0.5." Stevens Institute of Technology, Hoboken, NJ, USA. Released for public review 2011 on sebokwiki.org.

[4] A. Squires, and R. Cloutier. "Evolving the INCOSE reference curriculum for a graduate program in systems engineering." *Systems Engineering,* vol. 13, issue 4, pp. 381-388, 2010.

[5] M. Ardis, P. Bourque, T. Hilburn, K. Lasfer, S. Lucero, J. McDonald, A. Pyster, and M. Shaw, "Advancing Software Engineering Professional Education", *IEEE Software*, vol. 23, no. 6, pp. 58-63, July/August 2011.

[6] B.S. Bloom, B.S., M.D. Engelhart, E.J. Furst, W.H. Hill, and D. R. Krathwohl, *Taxonomy of educational objectives the classification of educational goals handbook I: Cognitive domain*. London, England: Longman Group Ltd., 1956.

[7] A. Squires, T. Ferris, D. Olwell, N. Hutchison, S.Enck, A. Pyster, and D. Gelosh, "Developing systems engineering graduate programs aligned to the body of knowledge and curriculum to advance systems engineering (BKCASE™) guidelines," in *Proceedings of the 2011 American Society for Engineering Education (ASEE) Annual Conference and Exposition*, Vancouver, BC, Canada, June 26-29, 2011.